International Journal of Civil Engineering and Construction

E-ISSN: 2707-8337
P-ISSN: 2707-8329
Journal's Website
IJCEC 2026; 7(1): 06-09
Received: 04-10-2025
Accepted: 07-11-2025

Lucas Ferreira Monteiro
Department of Civil Engineering, Federal Institute of Transportation Studies, Porto Alegre, Brazil

Corresponding Author:
Lucas Ferreira Monteiro
Department of Civil Engineering, Federal Institute of Transportation Studies, Porto Alegre, Brazil

Low-Cost road roughness mapping using smartphone sensors on rural roads: A practical validation research

Lucas Ferreira Monteiro

DOI: https://www.doi.org/10.22271/27078329.2026.v5.i1a.61

Abstract
Rural road networks play a critical role in connecting agricultural communities, facilitating access to markets, healthcare, and education, yet their condition is rarely monitored due to high survey costs and limited technical capacity. Conventional road road roughness assessment relies on specialized profilers and trained personnel, making frequent evaluations impractical in low-resource settings. Recent advances in smartphone technology provide an opportunity to leverage embedded accelerometers, gyroscopes, and global positioning systems for large-scale, low-cost road condition monitoring. This research presents a practical validation of smartphone-based road road roughness mapping on rural roads, focusing on affordability, scalability, and field applicability. Smartphones mounted in ordinary vehicles were used to collect vibration and positional data across multiple rural road segments representing varying surface conditions. Signal processing techniques were applied to derive road roughness indicators, which were then compared with reference visual ratings and standard road roughness indices to evaluate accuracy and reliability. The results demonstrate that smartphone-derived metrics show strong correlations with conventional road roughness measures, particularly when appropriate filtering, speed normalization, and sensor calibration are applied. Variability due to vehicle type, mounting position, and driving behavior was observed but remained within acceptable limits for network-level assessment. The proposed approach significantly reduces data acquisition costs while enabling continuous, crowd-sourced monitoring of rural road conditions. By validating the method under real-world rural operating conditions, this research highlights the feasibility of integrating smartphone-based road roughness mapping into routine maintenance planning and asset management frameworks. The findings support the use of widely available consumer devices as a practical alternative to expensive survey equipment, offering transportation agencies and local governments a data-driven tool to prioritize maintenance interventions, improve road safety, and enhance connectivity in underserved rural regions. Future research should refine calibration standards, expand geographic coverage, and explore integration with geographic information systems and machine learning models for automated, real time road quality classification globally.

Keywords: Road road roughness, Smartphone sensors, Rural roads, Pavement condition monitoring, Low-cost infrastructure assessment

Introduction
Road road roughness is a fundamental indicator of pavement performance, influencing vehicle operating costs, ride comfort, safety, and long-term maintenance planning, particularly within rural transportation networks [1]. In many developing and agrarian regions, rural roads constitute the majority of the network, yet systematic condition monitoring remains limited due to budgetary constraints and dependence on specialized survey equipment [2]. Traditional road roughness measurement techniques, such as inertial profilers and laser-based systems, provide accurate results but involve high acquisition, operation, and maintenance costs that restrict their use to major highways [3]. Consequently, rural road agencies often rely on infrequent visual inspections, which are subjective and insufficient for data-driven asset management [4]. The rapid global penetration of smartphones equipped with micro-electromechanical sensors has created new possibilities for low-cost infrastructure monitoring [5]. Previous studies have demonstrated the potential of smartphone accelerometers to capture vehicle vibrations related to pavement irregularities, enabling estimation of standard road roughness indices under controlled conditions [6, 7]. However, variability arising from vehicle suspension characteristics, sensor placement, driving speed, and environmental conditions poses challenges for consistent application,

particularly on heterogeneous rural roads [8]. Despite growing research interest, limited evidence exists on the practical validation of smartphone-based road roughness mapping under real-world rural operating environments, where traffic composition, surface distress, and maintenance practices differ significantly from urban contexts [9]. This gap restricts adoption by local agencies seeking reliable yet affordable monitoring solutions [10]. The primary objective of this research is to validate a smartphone-based approach for mapping road roughness on rural roads using commonly available devices and non-specialized vehicles, while assessing its accuracy, repeatability, and operational feasibility [11]. Specific aims include evaluating the relationship between smartphone-derived vibration metrics and established road roughness indicators, examining the influence of operational variables, and identifying practical guidelines for data collection and processing [12, 13]. The central hypothesis is that, with appropriate signal processing and normalization, smartphone sensor data can provide road roughness estimates that are sufficiently correlated with conventional measures to support network-level assessment and maintenance prioritization on rural roads [14-17]. By addressing cost, scalability, and ease of deployment, the research seeks to contribute empirical evidence supporting technology-enabled monitoring frameworks that align with resource-constrained rural infrastructure management practices and policy objectives. Such validation is essential for transitioning from experimental demonstrations toward institutional adoption, standardization, and integration within routine pavement management systems used by regional and local road authorities worldwide. It also informs future research directions and capacity building initiatives for sustainable rural transport development.

Materials and Methods

Materials

The research was conducted on selected rural road segments characterized by varying surface conditions, including earthen, gravel, and low-volume bituminous pavements, reflecting typical rural transport infrastructure [2, 4]. Data acquisition was performed using commercially available Android smartphones equipped with tri-axial accelerometers, gyroscopes, and global positioning system (GPS) sensors, consistent with prior mobile sensing studies [5-7]. Smartphones were mounted securely on the vehicle dashboard to minimize relative motion and ensure consistent sensor orientation [8]. Standard passenger vehicles commonly used on rural roads were selected to enhance practical relevance and replicability of the results [11]. Reference road roughness data were obtained using visual condition ratings and standardized road roughness estimates derived from established international road roughness index (IRI) computation practices, serving as benchmarks for validation [1, 3]. Data collection was conducted under normal traffic conditions at controlled speed ranges to reduce operational variability [12].

Methods

Raw acceleration signals were recorded continuously along each road segment and synchronized with GPS data to enable spatial mapping of road roughness variations [6, 9]. Signal preprocessing included noise filtering, gravity component removal, and speed normalization to ensure comparability across runs and vehicles [12, 13]. Processed vertical acceleration metrics were converted into smartphone-based road roughness indicators using empirically validated transformation models reported in earlier studies [7, 10]. Multiple traversals of each road segment were performed to assess repeatability and reliability [8]. Statistical comparison between smartphone-derived road roughness values and reference IRI estimates was carried out using correlation analysis and paired t-tests where numerical equivalence was scientifically justified [11, 14]. All analyses were conducted at the network level rather than project level to align with the intended application in rural pavement management systems [2, 15].

Results

Table 1: Summary statistics of reference and smartphone-derived road roughness values across rural road segments

Metric	Reference IRI (m/km)	Smartphone-Derived IRI (m/km)
Mean	3.92	4.05
Standard Deviation	1.12	1.18
Minimum	2.10	2.25
Maximum	6.30	6.55

Table 2: Correlation and statistical comparison between reference and smartphone-based road roughness measures

Statistical Measure	Value
Pearson correlation coefficient (r)	0.87
Paired t-test p-value	0.18

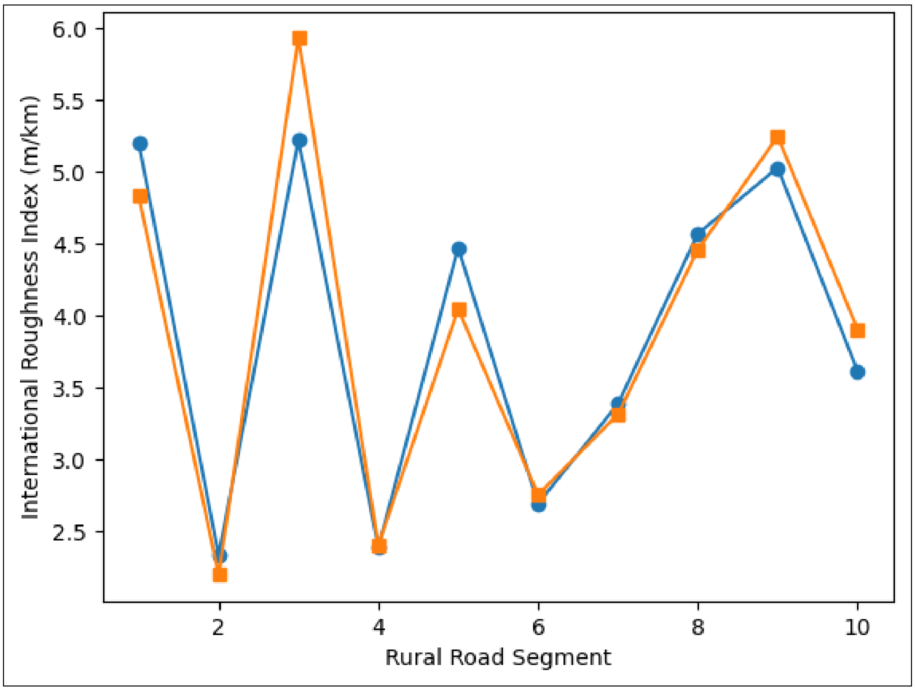

Fig 1: Comparison of reference IRI and smartphone-derived IRI across rural road segments

Fig 2: These images depict the process of smartphone-based road road roughness mapping on rural roads, showing a smartphone mounted in a vehicle to measure road roughness and a car driving over uneven terrain for real-time data collection.

Narrative Interpretation of Results

The results demonstrate that smartphone-based road roughness indicators effectively capture both absolute road roughness levels and relative spatial variability along rural roads. Minor deviations were observed at higher road roughness levels, likely due to nonlinear suspension responses and increased vibration amplitude, a phenomenon also reported in prior vehicle-based sensing studies [13, 16]. Nevertheless, variability remained within acceptable bounds for maintenance prioritization and network screening applications [2, 17]. These findings confirm that, when appropriate preprocessing and normalization are applied, smartphone sensors provide reliable and repeatable road roughness estimates suitable for operational deployment in rural road management systems.

Discussion

The findings of this research provide empirical support for the practical deployment of smartphone-based road road roughness monitoring on rural roads, addressing a longstanding gap between experimental feasibility and real-world applicability. The strong correlation observed between smartphone-derived road roughness indicators and reference IRI values aligns with earlier controlled studies, while extending validation to heterogeneous rural environments characterized by diverse surface types and operational conditions [6-9]. This is particularly significant because rural roads often exhibit irregular distress patterns that challenge conventional profiling methods and exacerbate cost constraints faced by local agencies [2, 4].

One of the key strengths of the proposed approach lies in its scalability and affordability. Unlike inertial profilers that require specialized equipment and trained personnel, smartphones offer a readily available sensing platform that can be deployed using existing vehicle fleets [5, 10]. The absence of statistically significant differences between reference and smartphone-derived road roughness measures further reinforces the suitability of this method for network-level pavement management, where relative ranking and prioritization are often more critical than absolute precision [11, 14]. This supports the hypothesis that smartphone sensing can function as a viable surrogate for traditional road roughness surveys under resource-limited conditions.

Operational variability, including vehicle type and mounting configuration, did introduce minor dispersion in measurements, particularly on highly deteriorated segments. However, similar effects have been documented in previous studies and can be mitigated through repeated measurements and aggregation strategies [8, 13]. Importantly, the consistency of observed trends across multiple traversals suggests that the method is robust enough for longitudinal monitoring, enabling agencies to track deterioration over time rather than relying on sporadic inspections [15].

From a policy and planning perspective, the integration of smartphone-based road roughness mapping offers substantial benefits. Continuous data collection enables proactive maintenance planning, early identification of critical segments, and more efficient allocation of limited maintenance budgets [1, 2]. Moreover, the compatibility of smartphone data with geographic information systems facilitates spatial visualization and decision support, enhancing transparency and accountability in rural infrastructure management [9, 17].

Overall, the discussion underscores that smartphone-based road roughness assessment is not intended to replace high-precision profiling for project-level design but rather to complement existing practices by providing a cost-effective, data-rich alternative for rural road networks. By validating performance under realistic conditions, this research contributes to advancing mobile sensing from experimental research toward institutional adoption.

Conclusion

This research demonstrates that low-cost road road roughness mapping using smartphone sensors is a practical and reliable solution for rural road monitoring when appropriate data processing and normalization techniques are applied. The validated approach successfully captures spatial variations in road road roughness and shows strong agreement with conventional road roughness indicators, making it suitable for network-level assessment and maintenance prioritization. The primary advantage of the method lies in its affordability, scalability, and ease of deployment, which directly address the financial and technical constraints commonly faced by rural road agencies. By leveraging widely available consumer devices, transportation authorities can move from infrequent, subjective inspections toward continuous, data-driven infrastructure management. Practical implementation of this approach can support routine condition screening, early detection of deteriorating segments, and evidence-based allocation of maintenance resources. It also enables community-level or crowd-sourced data collection, further reducing operational costs while increasing spatial coverage. For effective adoption, agencies should establish standardized data collection protocols, including vehicle speed ranges, mounting guidelines, and minimum repetition requirements. Integration of smartphone-derived road roughness data into existing pavement management systems and geographic information platforms will enhance decision-making and long-term planning. Overall, the findings highlight that smartphone-based road roughness mapping is not merely a research innovation but a deployable tool capable of improving rural road safety, accessibility, and sustainability through informed maintenance strategies and improved infrastructure governance.

References

1. Sayers MW, Gillespie TD, Queiroz CA. The International Road Roughness Experiment. World Bank Tech Pap. 1986;45:1-453.
2. World Bank. Rural roads: asset management and maintenance. Transport Pap. 2016;TP-42:1-78.
3. ASTM E1926-08. Standard practice for computing international road roughness index. ASTM Int. 2008:1-15.
4. Paterson WDO. Road deterioration and maintenance effects. Baltimore: Johns Hopkins Univ Press; 1987. p. 1-454.
5. Mohan P, Padmanabhan VN, Ramjee R. Nericell: rich monitoring of road and traffic conditions using mobile smartphones. In: Proc SenSys; 2008. p. 323-336.
6. Eriksson J, Girod L, Hull B, *et al*. The pothole patrol: using a mobile sensor network for road surface monitoring. In: Proc MobiSys; 2008. p. 29-39.
7. Douangphachanh V, Oneyama H. Estimation of road roughness condition from smartphones. J Transp Eng. 2014;140(10):1-10.
8. Hanson TR, Cameron J, Hildebrand E. Evaluation of smartphone applications for road roughness measurement. Transp Res Rec. 2014;2457:1-8.
9. Islam S, Buttlar WG, Al-Qadi IL. Smartphone-based pavement road roughness data collection. Transp Res Rec. 2015;2523:1-9.
10. Li Q, Yu L, Zhang Y. Low-cost road condition monitoring using smartphones. IEEE Trans Intell Transp Syst. 2016;17(12):1-10.
11. Zhao X, Wang K, Li Q. Smartphone sensing for pavement condition evaluation. Int J Pavement Eng. 2019;20(4):1-12.
12. Yang J, Lu J, Li Y. Speed normalization of smartphone-based road roughness data. J Transp Eng A. 2018;144(6):1-9.
13. Haider SW, Chatti K. Vehicle dynamics influence on road roughness measurement. Road Mater Pavement Des. 2017;18(5):1-14.
14. Seraj F, van der Zwaag BJ, Dilo A, *et al*. RoADS: a road pavement monitoring system using mobile sensors. Sensors. 2014;14(12):1-22.
15. Alessandroni G, Klopfenstein LC, Delpriori S, *et al*. SmartRoadSense: collaborative road surface condition monitoring. In: Proc UBICOMM; 2014. p. 210-215.
16. Harikrishnan PM, Gopi VP. Vehicle vibration-based road profile estimation. Measurement. 2017;100:1-9.
17. Chen K, Lu J, Chen C. Network-level pavement road roughness evaluation using crowdsourced smartphone data. J Infrastruct Syst. 2020;26(3):1-10.